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ABSTRACT

Improvements in building end-use efficiency have significantly reduced the energy intensity of new buildings, but diminishing returns make cost-effective zero-net energy (ZNE) buildings a challenge. A largely untapped efficiency strategy is to improve the efficiency of power distribution within buildings. Direct current (DC) distribution with modern power electronics has the potential to eliminate much of the power conversion loss in alternating current (AC) building distribution networks. Previous literature suggests up to 15% energy savings in DC ZNE buildings with onsite generation and battery storage. Nonetheless, DC faces a market disadvantage against AC, and the benefits of DC distribution must be compellingly demonstrated before wide adoption. This paper presents recent modeling of DC vs. AC distribution in buildings, based on detailed load and generation profiles, wire losses, and power conversion efficiency curves. Our analysis shows that annual energy savings can range from approximately 8% of baseline electricity use in an office with PV and no battery, to approximately 15% in a building with a large PV array and battery. This paper also presents a techno-economic analysis framework that evaluates the cost-effectiveness of DC systems in several commercial buildings based on commercially available products. Based on a Monte Carlo analysis, we find that DC systems can be cost effective in all scenarios that include battery storage and onsite solar, whereas for systems without storage, DC distribution is not cost effective.

Introduction

Zero-net energy (ZNE) buildings, which combine greatly reduced energy use with on-site renewable generation, are becoming more common and will be required by future building codes in California and other jurisdictions. Achieving ZNE cost-effectively, however, is difficult for some commercial buildings with today's end-use efficiency technologies. An efficiency strategy that is largely untapped is to improve the efficiency of power distribution and conversion within buildings. Direct current (DC) power distribution can lead to electricity savings due to avoided power conversions between DC and alternating current (AC) power in buildings that have on-site solar generation and a significant share of equipment that is internally DC powered. Several studies, summarized by Vossos et al. (2017), have estimated or measured the energy savings from DC distribution, with savings ranging from a few percent to about 15 percent. Several factors influence these energy savings, including the configuration of the building distribution system, the presence of battery storage, the coincidence of electric load usage and PV generation, and the relative efficiency of power converters in the DC vs. AC distribution system.

DC distribution has had successful commercial application in data centers (AlLee and Tschudi 2012; Geary 2012). In addition, DC is beginning to gain traction in commercial buildings for lighting applications, with several companies offering DC-powered luminaires and DC lighting systems. Despite these developments, the market for DC in buildings faces significant barriers, such as the lack of available DC-ready appliances and distribution system components (converters, plugs, circuit breakers, etc.), the relative immaturity of technology standards, and lack of awareness among building owners, designers, and operators. On the other hand, DC distribution can possibly have lower capital cost, due to power systems with fewer converters[1], appliances with simpler power electronics, and power and communications shared by the same wiring (Vossos et al. 2017).

A relatively small but growing number of studies have addressed the cost-effectiveness of DC distribution in buildings, compared to the standard AC. DC distribution systems are most beneficial for powering building equipment whose internal components operate natively on DC, such as variable speed brushless DC (BLDC) air conditioners (Glasgo, Azevedo, and Hendrickson 2016), and LED lighting (Thomas, Azevedo, and Morgan 2012). These types of equipment tend to be more energy efficient and are often found in ZNE buildings, making DC power an even better match for ZNE. Several other studies compare the relative cost difference of power system components and appliance converters in AC vs. DC buildings (Willems and Aerts 2014; Sannino, Postiglione, and Bollen 2003). Direct-DC is claimed to potentially improve power supply cost by 55%, efficiency by 50%, and weight and volume by 70% (Wunder et al. 2014; Rodriguez-Diaz, Vasquez, and Guerrero 2017). Finally, several future-scenario studies found that DC distribution can be especially cost-effective in newly constructed ZNE buildings, assuming the cost of DC products is significantly reduced through production volumes and market maturation (Foster Porter et al. 2014, Denkenberger et al. 2012, Fregosi et al. 2015).

Although DC distribution systems currently have higher initial capital costs than AC systems, their electricity savings could outweigh those costs and yield desirable payback in certain use cases. One such use case is high-efficiency commercial buildings with onsite PV, due to the high fraction (over 60%) of their energy consumed as electricity (EIA 2017), and the high coincidence of solar generation and commercial end-use loads. This helps explain why much of the early adoption of DC distribution systems has been in commercial buildings, primarily for lighting applications.

[1] It is important to note that while DC loads do not require AC-DC conversion, they may require a DC-DC converter if their internal DC voltage is not well-matched to the distribution voltage.

This paper extends previous work conducted by Gerber et al. (2018), to model three medium sized commercial buildings in San Francisco, while parametrically varying the solar generation and battery storage capacity to find economically optimal values. We use Monte Carlo simulation to account for uncertainty and variability in the cost inputs, and compute the payback period (PBP) and lifecycle cost (LCC) savings for DC compared to AC systems. The rest of the paper first discusses the methodology and model inputs, including the distribution system design. It then presents the results of the efficiency and techno-economic (TEA) analysis, and concludes with a discussion of policy implications and recommendations for future work. This work improves on previous research by examining a wider range of building types, modeling the building power distribution system in more detail, and using actual electricity tariffs.

Methodology and Model Inputs

Modeled Buildings

We analyze three small to medium size commercial buildings (ranging in floor area from 500 to 5,000 square meters) in San Francisco, drawing building dimensions and load profiles from the 90.1-2013 EnergyPlus reference buildings (Deru et al. 2011; DOE 2017). These buildings are a medium office building, a full-service restaurant, and a stand-alone retail space, and are selected to capture a variety in load types and load profiles. Hourly electrical load data are estimated using EnergyPlus for the following electrical end uses: Heating, cooling, fans, pumps, interior lighting, exterior lighting, interior equipment, and refrigeration, the latter for the restaurant only. All buildings are low-rise, which makes them ideal for onsite PV systems.

Building Distribution Systems and Loads

Diagrams for the AC and DC electrical systems are shown inError: Reference source not found and Error: Reference source not found, respectively. The building models utilize one or more of the following power distribution voltages:

- AC Building: 120 V single phase and 208 V three phase
- DC Building: 380 V DC (high voltage) 48 V DC (low voltage)

In the building model, the electrical sources and sinks are the PV generation and the end-use equipment, respectively. The battery and grid connection can bidirectionally source or sink power. Electrical losses are attributed to converters, building distribution wiring, and chemical losses in the battery. The building model assumes that the electrical end uses in the AC and DC building are identical (all are internally-DC), and they have the same layout and usage profiles. PV generation data for each building are derived from PVWatts (NREL 2017). The simulation models, inputs, and assumptions for each component are discussed in detail in Gerber et al. (2018).

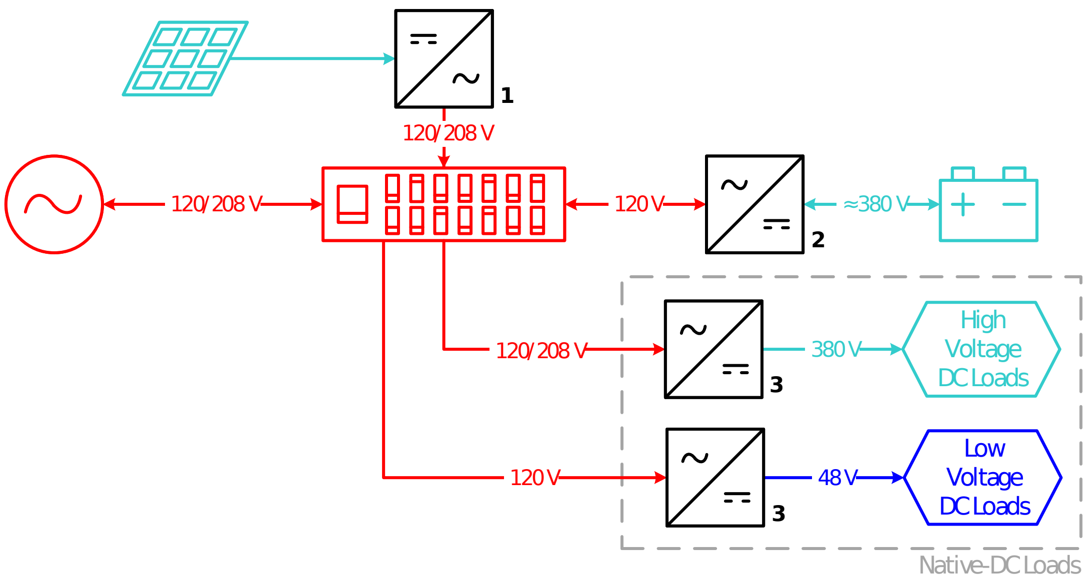


Figure 1. Building network with AC distribution. Converters: 1. string inverter (performs maximum power point tracking), 2. battery inverter (performs bidirectional charge control), 3. load-packaged rectifier or wall adapter.

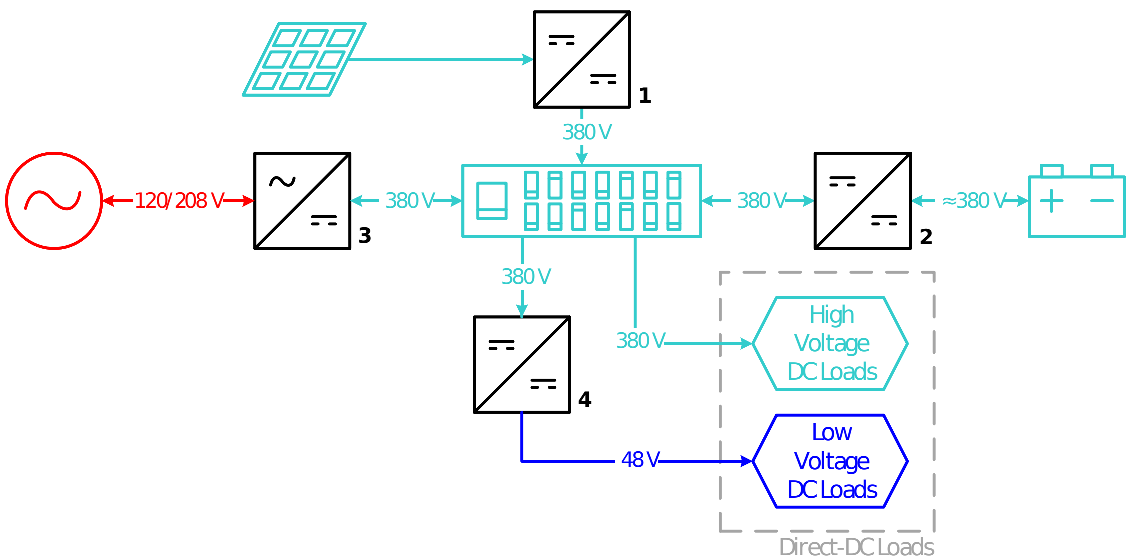


Figure 2. Building network with DC distribution. Converters: 1. Maximum power point tracking (MPPT) module (performs maximum power point tracking), 2. battery charge controller (performs bidirectional charge control), 3. grid tie inverter (bidirectional), 4. DC-DC step-down, which could be a 48 V power server. Certain loads such as LEDs require an additional DC-DC converter (not shown).

As discussed in Garbesi, Vossos, and Shen (2011), the most efficient electricity end uses are internally DC. Therefore, similar to the analysis by Gerber et al. (2018; 2017), and to minimize losses for the DC distribution system, the building model assumes that all electric loads can be supplied directly with DC power. In this sense, the loads are optimally designed such that their internal DC voltage is matched to the distribution. In addition, the battery is controlled so as to minimize grid interaction (i.e. charge with excess PV and discharge when load exceeds PV).

Parametric Selection of PV and Battery Sizing

This study uses parametric analysis to determine the energy and economic conditions in which DC distribution is favorable. We examined six parametric runs for each building, in which the solar and battery capacity are varied relative to their baseline values. The baseline solar capacity is the amount that will generate enough energy on an annual basis to equal the building's annual energy consumption, thus qualifying the building as zero net electricity (ZNe). Note that the reference buildings in this study are not zero net energy, since the solar generation does not cover for the natural gas loads. The baseline battery capacity is derived from the baseline solar capacity and is equal to half the capacity required to store all the excess PV (difference between daily generation and load) on the sunniest day of the year. In San Francisco, this capacity can actually store all of the excess PV on nearly 80% of the days. The battery capacity is set to either zero, half-baseline, or baseline, while the solar capacity is set to either its half-baseline or baseline value.

Techno-economic Analysis Methodology

To evaluate the cost effectiveness of the DC distribution, we compare its economic performance to a corresponding AC distribution system. This comparison considers the incremental cost difference between these two systems, under the assumption that the AC and DC buildings are the same other than their distribution systems. Thus, the TEA is limited to capital and operating cost differences due to different system components in the AC and DC distribution systems. The methodology and metrics used in this TEA are consistent to those used by the United States Department of Energy (DOE) to determine consumer economic impacts of energy conservation standards to appliances (Rosenquist et al. 2004). The life cycle cost (LCC) is calculated according to the following equation:

$$LCC = Total\,Installed\,Cost + Lifetime\,Operating\,Cost \quad \textbf{(1)}$$

The total installed cost includes the cost of the building distribution system and costs of electrical end-use equipment. Installation costs and other soft costs, such as permitting and design costs, are ignored in this analysis due to lack of data. The lifetime operating cost represents the present value of the system's operating cost, which includes any maintenance and repair costs, over its lifetime. The lifetime operating cost is calculated according to the following equation:

$$Lifetime\,Operating\,Cost = \sum_{y=1}^{Lifetime} \frac{Operating\,Cost(y)}{(1+r)^y} (2)$$

The payback period (PBP) is the time required for the DC system's energy savings to pay back its higher installation cost. It is calculated according to the following equation:

$$PBP = \frac{Total\,Installed\,cost_{DC} - Total\,Installed\,cost_{AC}}{Annual\,Operating\,cost_{AC} - Annual\,Operating\,cost_{DC}} (3)$$

Figure 1 shows a flow diagram of inputs and outputs for the LCC and PBP calculations.

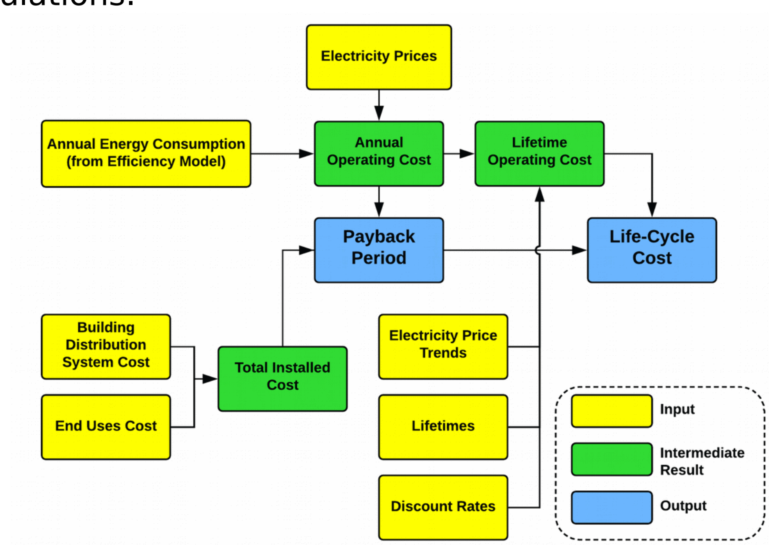
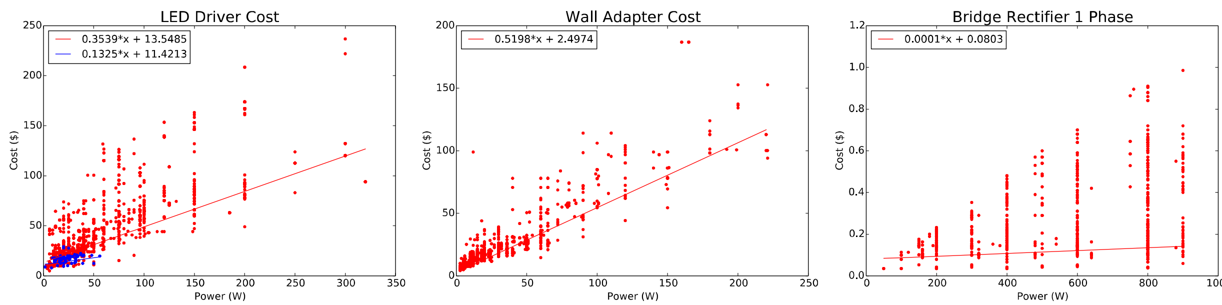


Figure 1. LCC and PBP flow diagram

The TEA is performed by running 1,000 Monte Carlo simulations for each scenario, to account for input uncertainty and variability. The simulations are conducted using Microsoft Excel and Crystal Ball, a commercially available Excel add-in software.

Techno-economic Analysis Inputs

To determine the total installed cost of each system, we first estimate the cost of a building's major electrical infrastructure, including circuit breakers and all the components shown in Figure 1 and Figure 2. Infrastructure component costs are derived from online retailers, distributors, and manufacturer estimates. For end-use equipment, the cost difference between DC and AC is attributed to specific electrical components that differ between the two distribution types: AC and DC LED drivers for lighting, wall adapters for electronics, and bridge rectifiers for high power loads, such as HVAC and refrigeration. We developed cost vs. power functions based on online cost data from digikey.com, as shown in Figure 4.



(a) (b) (c)

Figure 4. Cost data and linear regressions for (a) LED drivers, (b) wall adapters, and (c) bridge rectifiers. Components required in an AC and DC system are shown in red and blue, respectively. Source: Digikey.com

The distribution of wattages for the AC and DC LED drivers (and therefore, their costs) was determined by utilizing the distribution of LED luminaire types and their corresponding wattages for each of the analyzed buildings, according to Table D.3 and D.4 of the 2015 U.S. Lighting Market Characterization (Navigant Consulting, Inc. 2017). To determine the distribution of load types for electronics, we identified such end uses for the office and retail building (the restaurant was assumed to not include electronic loads) in the 2012 Commercial Buildings Energy Consumption Survey (CBECS) (EIA 2017) and estimated wattage ranges for these loads based on various sources (Urban et al. 2017; FEMP 2018).

To determine system lifetime operating costs, we first utilize the results of the efficiency analysis, which derives the annual electricity use of each building, and apply the Pacific Gas & Electric A-1 electric rate schedule[2] for small general commercial service (PG&E 2018) to compute annual electricity bills. We then estimate future electricity prices by applying electricity price trends based on EIA's Annual Energy Outlook 2018 (AEO 2018) and derive the present value of future costs by applying discount rates specific to each building type. Note that building electrical equipment lifetimes are assumed to be 10 years on average. Error: Reference source

[2] The A-1 rate does not include a demand charge

not found lists cost ranges and sources for each of the power system components, as well as other inputs included in the TEA.

Table 1. Summary of Techno-Economic Analysis Inputs

Parameter	Minimum/ Default Value	Maximum Value	Unit	Source
First Cost Parameters				
AC inverter cost	190	290	$/kW	Civicsolar.com, altestore.com
AC battery inverter cost	370	660	$/kW	Civicsolar.com, stratensolar.com
DC optimizer cost	100	220	$/kW	stratensolar.com, distr. quotes
DC grid-tie inverter*	370	660	$/kW	Civicsolar.com,stratensolar.com
DC 380-48 V converter	250	450	$/kW	Distributor quotes
AC circuit breaker (20A)	16	18	$/unit	mouser.com
DC circuit breaker (20A)	30	36	$/unit	mouser.com
AC LED driver	Cost-power regression, ±10%		$/unit	digikey.com
DC LED driver	Cost-power regression, ±10%		$/unit	digikey.com
AC wall adapter cost	Cost-power regression, ±10%		$/kW	digikey.com
Sales tax	8.5%		%	thestc.com
Operating Cost Parameters				
Distr. Syst. Efficiency	Varies		%	Efficiency analysis
System lifetime	8	12	years	Typical equip. lifetimes
Office discount rate	5.05% with 1.05 std deviation		%	Damodaran online
Restaurant discount rate	6.07% with 0.92% std deviation		%	Damodaran online
Retail discount rate	5.63% with 1.05% std deviation		%	Damodaran online
Electricity prices	Varies by time-of-use rate		$/kWh	PG&E
Electricity price trends	94% - 114% of base year price		%	AEO 2018
Monte Carlo Simulation Parameters				
Number of simulations	1000 runs			

* The cost of the DC grid-tie inverter (bidirectional) was assumed to be similar to the cost of the battery inverter. The bidirectional inverter is also assumed to include battery charge control.

Results

Efficiency Results

In each parametric run, the DC building has lower electrical losses than the AC building, as shown in Figure 5 for the medium office building. The reduced losses due to DC distribution increase for buildings with larger solar and battery capacity, shown as the scenarios progress to the right in Figure 5. We only show the medium office building here, because the restaurant and retail all had similar loss breakdowns, with any differences caused by the distribution of the type of end-use equipment and the wiring configuration in each building type. The analysis shows that energy savings can range from approximately 8% in an office with PV and no battery, to approximately 15% in an office with a large PV array and battery.

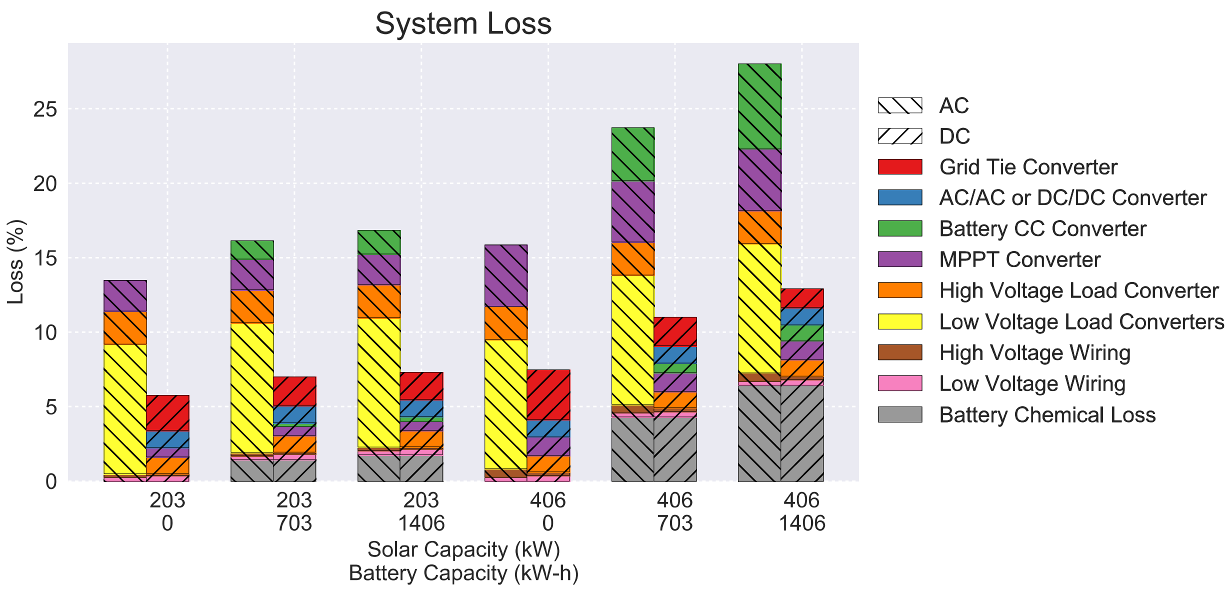


Figure 5. Energy simulation loss analysis results for the medium office building. The other buildings have a similar loss breakdown. The most significant loss in each building is from low-voltage AC load converters, which include internal power supply rectifiers and wall adapters.

Techno-Economic analysis results

As shown in Table 2, below, DC systems have positive LCC savings and payback periods of four years or less in all scenarios that include battery storage. For buildings with large PV arrays and battery storage systems, DC systems actually have lower first cost than their corresponding AC systems, leading to instant payback periods. This is due primarily to the relative cost of the DC vs. AC system power system components e.g., the cost of the DC optimizer ($100 - $220 per kWh) vs. the cost of the inverter ($190 - $290 per kWh) and their high capacity which dominates the cost of the system. However, for systems without battery storage, DC distribution has negative LCC savings for more than 75% of simulation runs in all buildings, and payback periods ranging between 10 and 28 years.

Figure 6 shows an example histogram of the LCC savings for the medium office building, in the 100% PV, 50% battery scenario. In this scenario, about 4% of simulation runs yield negative LCC savings.

Table 2. Techno-Economic Analysis Results

Medium Office Building						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	93,000	190,000	212,000	152,000	272,000	331,000
DC First Cost ($)	245,000	245,000	245,000	365,000	334,000	332,000
AC LCC ($)	843,000	973,000	1,006,000	300,000	530,000	660,000
DC LCC ($)	894,000	911,000	917,000	412,000	439,000	479,000
Mean LCC Savings ($)	-57,000	56,000	83,000	-112,000	90,000	181,000
% Simulations with Positive LCC Savings	3.0%	94.3%	99.1%	0.3%	96.8%	100.0%
Mean PBP (years)	13.0	4.0	2.3	17.2	3.3	0.0
Retail						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	47,000	88,000	93,000	79,000	132,000	171,000
DC First Cost ($)	170,000	170,000	170,000	191,000	191,000	191,000
AC LCC ($)	418,000	480,000	486,000	139,000	237,000	311,000
DC LCC ($)	494,000	504,000	505,000	202,000	226,000	248,000
Mean LCC Savings ($)	-79,000	-27,000	-21,000	-63,000	11,000	64,000
% Simulations with Positive LCC Savings	0.0%	14.9%	21.8%	0.3%	64.7%	98.2%
Mean PBP (years)	21.1	11.4	10.6	17.3	6.4	1.9
Restaurant						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	30,000	62,000	66,000	56,000	98,000	134,000
DC First Cost ($)	57,000	57,000	57,000	127,000	115,000	99,000
AC LCC ($)	327,000	379,000	384,000	104,000	180,000	251,000
DC LCC ($)	312,000	322,000	323,000	133,000	138,000	143,000
Mean LCC Savings ($)	14,000	56,000	60,000	-29,000	42,000	109,000

% Simulations with Positive LCC Savings	92.9%	100.0%	100.0%	5.7%	98.8%	100.0%
Mean PBP (years)	4.9	0	0	12.6	2.1	0

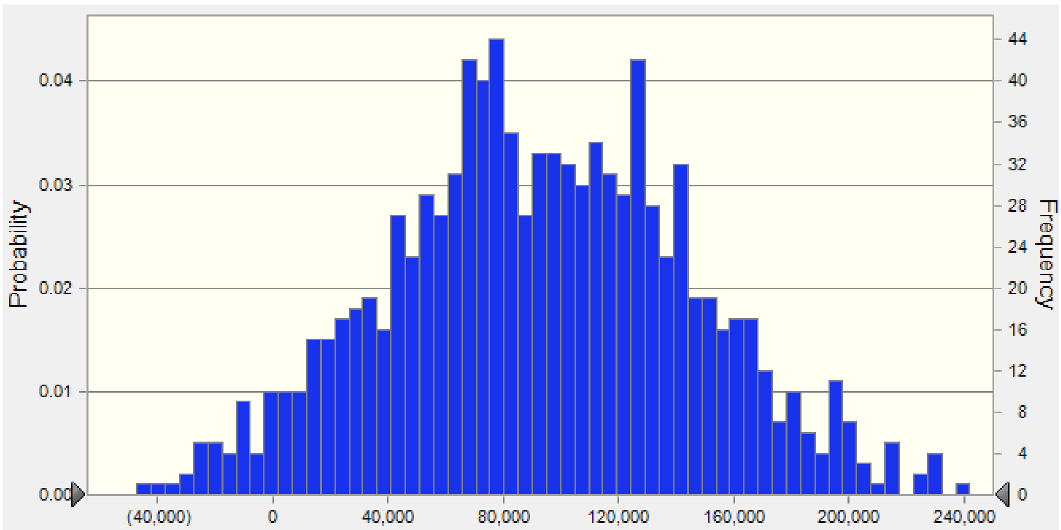


Figure 6. Distribution of LCC savings for the Medium Office Building, in the 100% PV, 50% battery scenario. About 4% of simulation runs yield negative LCC savings.

Conclusions and Discussion

This paper analyzed the energy savings and cost-effectiveness of DC power distribution in small and medium commercial buildings with ZNE designs in San Francisco, including on-site solar and batteries. Input data for the analysis were, as much as possible, collected from commercially available products, including energy performance and purchase prices. We modeled annual energy use for an office building, retail store, and restaurant, both with standard AC power distribution and direct DC distribution. Our analysis shows that annual energy savings can range from approximately 8% of baseline electricity use in an office with PV and no battery, to approximately 15% in an office with a large PV array and battery. Based on a Monte Carlo analysis to assess the cost-effectiveness of DC distribution compared to the AC baseline, we find that the DC systems are cost effective in all scenarios that included battery storage, whereas in those scenarios that did not, DC systems were not cost effective.

The purpose of this analysis was to present an analytical framework on the economic evaluation of DC distribution in commercial buildings based on available data. This analysis does not address whether commercial buildings with battery storage are cost effective compared to those without, but it is focused on the AC vs. DC distribution comparison. For any climate zone similar to San Francisco, DC distribution makes sense economically in commercial buildings with large battery storage systems and onsite PV arrays. We should also note that the current market for DC systems is at its nascent stage, therefore costs not considered in this analysis, such as installations costs, permitting costs, and other soft costs are expected to be higher for DC systems in the short run. Overall, we conclude that once awareness barriers and more direct-DC products become available, DC systems could be cost-effective in small and medium commercial buildings.

Acknowledgements

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